

# Anomalous Pulsars

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## Abstract

Many astrophysicists believe that Anomalous X-Ray Pulsars (AXP), Soft Gamma-Ray Repeaters (SGR), Rotational Radio Transients (RRAT), Compact Central Objects (CCO) and X-Ray Dim Isolated Neutron Stars (XDINS) belong to different classes of anomalous objects with neutron stars as the central bodies inducing all their observable peculiarities. We have shown earlier (I.F.Malov and G.Z.Machabeli, *Astron. Astrophys. Trans.* 25 7, 2006) that AXPs and SGRs could be described by the drift model in the framework of preposition on usual properties of the central neutron star (rotation periods  $P \sim 0.1 - 1$  sec, surface magnetic fields  $B \sim 10^{11} - 10^{13}$  G). Here we shall try to show that some differences of considered sources will be explained by their geometry (particularly, by the angle  $\beta$  between their rotation and magnetic axes). If  $\beta \lesssim 10^\circ$  (the aligned rotator) the drift waves at the outer layers of the neutron star magnetosphere should play a key role in the observable periodicity. For large values of  $\beta$  (the case of the nearly orthogonal rotator) an accretion from the surrounding medium (for example, from the relic disk) can cause some modulation and transient events in received radiation.

Key words: AXP, SGR, RRAT, radio pulsars: drift waves, relic disk, accretion PACS: 97.60.Gb, 97.10.Kc

## 1 Introduction

During the last decades the interest to some X-ray sources has grown drastically. These are first of all AXPs and SGRs, "magnetars" as many investigators believe. We showed in our paper [1] that these objects could be described by the drift model, and the usual neutron star lied in the base of both types of sources. The drift waves cause some changes of magnetic field lines curvature and as the consequence the modulation of emission propagation directions (Fig.1). The calculations in the framework of this model have been carried out. As the result some parameters of neutron stars in the known AXPs and SGRs were obtained: the interval for the rotation periods is  $P = 11 - 737$  msec, for their derivatives  $dP/dt = 3.7 \times 10^{-16} - 5.5 \times 10^{-12}$ , and for the surface magnetic fields  $\log B_s = 11.22 - 13.24$ . The main difference between AXPs / SGRs and normal radio pulsars is a small inclination of the magnetic moment to the rotation axis in the first group. The corresponding angle  $\beta$  must be of order to (or less than)  $10^\circ$ . We believe that all neutron stars with  $\beta \lesssim 10^\circ$  must belong to the population with observed intervals between successive pulses (if they are seen)  $P_{obs}$  of order to several seconds. For example, so called high magnetic field pulsars are the objects of this type. Real rotation periods and magnetic fields for pulsars with very long observed pulse periods are the same as for normal pulsars [2]:  $P = 0.5 - 1.12$  sec,  $B_s = (0.2 - 16)10^{12}$  G. Fig. 2 and 3 show some details of the drift model.

Table 1: Radio transients

Name	P (sec)	$w_{50}/P$ %	$dP/dt$ $10^{-15}$	B $10^{12}$ G	$\tau$ $10^6$ years	$dE/dt$ $10^{31}$ erg /sec
J0848-43	5.97748(2)	0.50	- - - -			
J1317-5759	2.6421979742(3)	0.38 12.6(7)	5.83(2)	3.33(2)	2.69(1)	
J1443-60	4.758565(5)	0.42	- - - -			
J1754-30	0.422617(4)	3.79	- - - -			
J1819-1458	4.263159894(6)	0.07 576(1) 50.16(6)	0.1172(3)	24.94(5)		
J1826-14	0.7706187(3)	0.26	- - - -			
J1832+0031						
J1839-01	0.93190(1)	1.61	- - - -			
J1846-02	4.476739(3)	0.36	- - - -			
J1848-12	6.7953(5)	0.03	- - - -			
J1911+00						
J1913+1333	0.9233885242(1)	0.22	7.87(2)	2.727(4)	1.860(6)	39.4(1)
B1931+24	0.813690303	5	7.15-10.79	2.6	1.6	$5.9 \cdot 10^{-6}$
J1649+2533	1,0152573918(5)	2,46	0,5594(2)	0,79	28,7	2
J1752+2359	0,409050865044(9)	0,98	0,6427(9)	0,5	10,1	39,81
B0656+14	0.384885	7.7	55.01	4.68	0.11	72.44
J1745-3009	4627.8					

## 2 Radio transients

There were discovered new types of objects during the last dozen years. These are transients, i.e. sources emitting suddenly a few number of pulses and then being switched off. The table 1 contains the list of such sources and possible candidates [3-8].

To explain transient character of emission from these objects some models were put forward during the last few years.

1. Precession of pulsars with long time nullings [9]. To achieve the agreement with observations it is necessary to suggest in this model large angles of precession ( $\gamma > 15^\circ$ ).  $\gamma$  is the angle between the rotation axis and the angular momentum. The estimations give for normal radio pulsars  $\gamma < 10^\circ$ . The required precession in neutron stars is possible for very large deformations only and can be realized at rotation periods of order to 1 msec. Moreover this precession must quickly damp (during  $10^2 - 10^4$  periods of the precession). To avoid these difficulties the authors propose to use as the host object in such pulsars a solid quark star with possible large elastic deformations. However the existence of quark stars is rather problematic, and their corresponding models have not been worked out up to now.

2. Zhang et al. [10] considered the possibility of the location of a pulsar near and below the "death line" and irregular appearances of the pulsar above this line. Such appearances take place when the magnetic field of the solar spot type comes to the surface and induces the process of  $e^\pm$  - pairs creation. What is the real equation of the death line is unclear yet. If take the equation used by the authors some transients find themselves above this line, and other mechanism of switching off of their radiation must operate.

3. The same authors [10-11] considered the another possibility to explain RRATs. They put forward the idea of so called inward radiation, i.e. radiation directed opposite to usual "right" pulsar radiation, and connected nullings with this emission directed inward. In this model the geometric effects play role only and the breaking

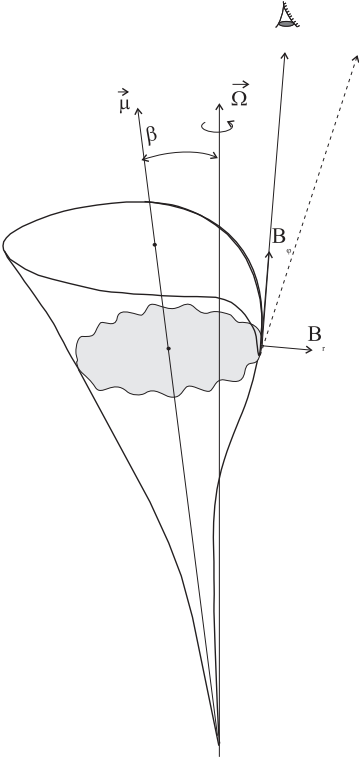


Figure 1: Scheme of the drift model.  $\mu$  is the magnetic moment,  $\Omega$  is the rotation axis.

must be the same in "on" and "off" phases. So, some other mechanisms must operate at least in PSR B1931+24, where the frequency derivatives differ significantly (1.5 times) in these two phases (Fig.4). Similar behaviour shows PSR J1832+0031[8] (Fig.5).

4. The long period ( $77^m$ ) of the source J1745-3009 near the Galactic Center excludes a neutron star as the central body because the losses of its rotation energy  $dE/dt$  are very low ( $\sim 10^{22}$  erg/sec) to provide the observable luminosity. Zhang & Gil [12] proposed to consider a white dwarf as a pulsar. It must have a complicated magnetic field at the surface (like the field of solar spots) inducing an irregular creation of  $e^\pm$ -pairs. However there is no known white dwarfs with pulsar characteristics. Moreover the rotation period ( $\sim 77^m$ ) is of order to minimal values for such objects, and the magnetic field must be extremely high ( $\sim 10^9$  G).

5. Turrola et al.[13] have tried to explain the source J1745-3009 in the framework of the binary system with the orbital period ( $77^m$ ). It was proposed that this system consists of two neutron stars and is similar to the system of the pulsar J0737-3039. Its coherent radio emission is generated in the shock wave due to an interaction between the wind from the more energetic pulsar and the magnetosphere of its companion. The modulation of emission is caused by the orbit eccentricity and connected with periodic penetration of the wind in the inner layers of the companion magnetosphere. However this model can be realized for eccentricities  $e = 0.4$  and can not explain the lack of emission in the time interval between the consequence bursts. Moreover both neutron stars in such a system must be rather powerful pulsars with periods  $0.3 - 1$  sec. The question arises why they are not observed. If a pulsar in this system will be detected this model will be tested by the change of the

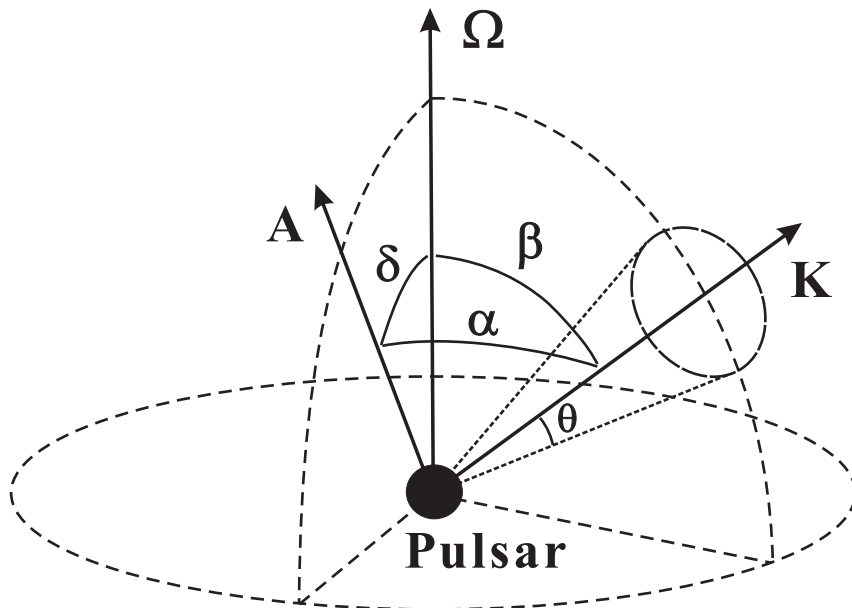


Figure 2: Geometry of the drift model.  $\mathbf{K}$  is the axis of the emission cone,  $\mathbf{A}$  is the direction to the observer.  $\delta = \text{Constant}$ ,  $\theta = \text{Constant}$ ,  $\alpha$  and  $\beta$  are functions of time.

period with time.

#### 6. Drift model.

In this model [14] the line of sight could find itself sometimes inside of an emission cone due to cataclysms at the surface of the neutron star. It is suggested that the angle  $\beta$  between the rotation axis and the magnetic moment is small enough. A very narrow pulse is expected in this case. This pulse must contain odd number of extremely narrow sub-pulses (1, 3, 5 or more with smoothly falling intensities) (Fig.3,6). To be seen during milliseconds such transient must have very short rotation period.

7. Li [15] put forward the model of a relic disk retained after the supernova explosion or formed from the captured interstellar matter. The neutron star operates as a propeller when the disk penetrates inside the light cylinder and quenches the generation of the of  $e^\pm$  - plasma. An emission is switched on if disk goes out the light cylinder. In one case the braking is caused by the magneto-dipole radiation, in the another one an additional moment is taken away by the pulsar wind, and the pulsar is slowing down faster.

Wang et al. [16] detected IR radiation from the cold disk around the isolated young X-ray pulsar 4U 0142+61. This is the first evidence of the disk-like matter around the neutron star.

A surrounding plasma and a braking connected with it can explain relatively long rotation periods comparing with normal radio pulsars.

In this model the angle  $\beta$  is expected to be high.

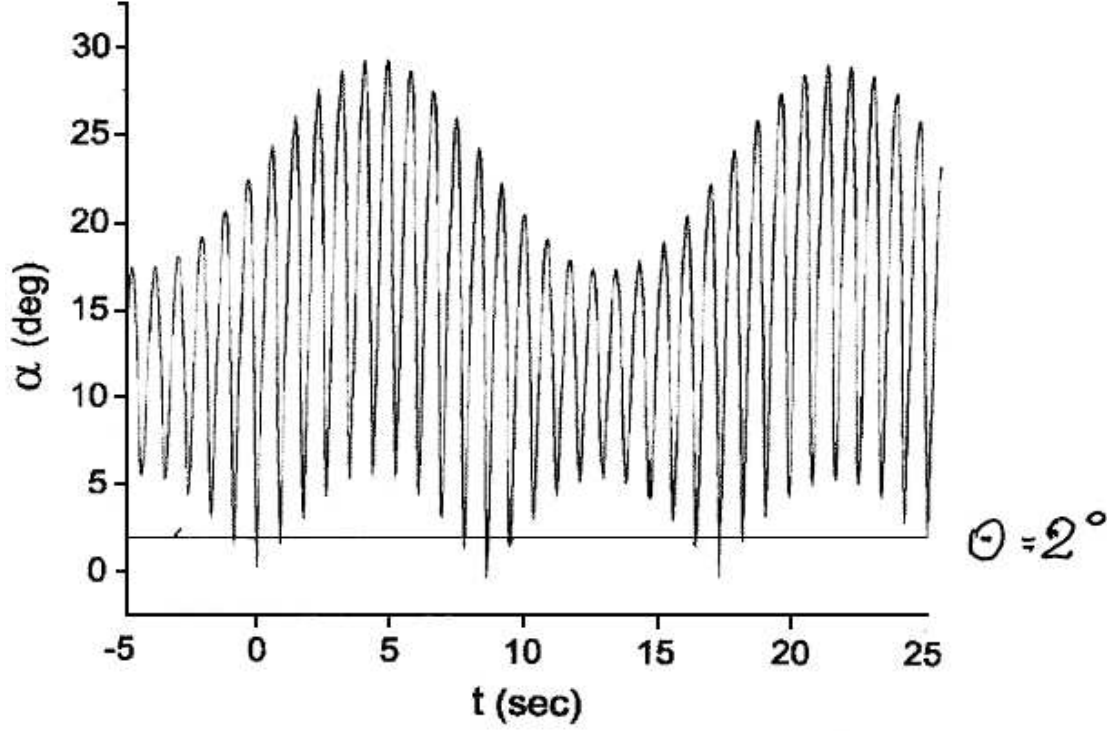


Figure 3: The oscillating behaviour of  $\alpha$  with time for  $\Omega = 2\pi/0.85\text{sec}^{-1}$ ,  $\Theta = 2^\circ$ .

### 3 Angles between rotation and magnetic axes

As we declared in the previous section, the angle  $\beta$  between the rotation axis of the given object and its magnetic moment was very important for the choosing of the adequate model. Here we will discuss some possibilities of the evaluation of this angle for a number of sources under consideration.

Using a schematic presentation of the radiation-cone geometry (Fig.7), we can write three following equations [18]:

$$\begin{aligned} \sin \beta &= C \sin(\zeta - \beta), \\ \cos \theta &= \cos \zeta \cos \beta + D \sin \beta \sin \zeta, \\ \theta &= n(\zeta - \beta) \end{aligned} \tag{1}$$

for three unknowns: the angle  $\beta$  between the rotation axis ( $\mathbf{\Omega}$ ) and the magnetic moment ( $\vec{\mu}$ ), the angle  $\zeta$  between the line of sight ( $\mathbf{L}$ ) and  $\mathbf{\Omega}$ , and the angular radius  $\theta$  of the radiation cone, assuming that it is connected to open magnetic-field lines.

In (1)  $n$  is the fraction of the angular radius of the cone where the line of sight passes and

$$C =_{\zeta} d\psi/d\Phi_{max} = \sin \beta / \sin(\zeta - \beta) \tag{2}$$

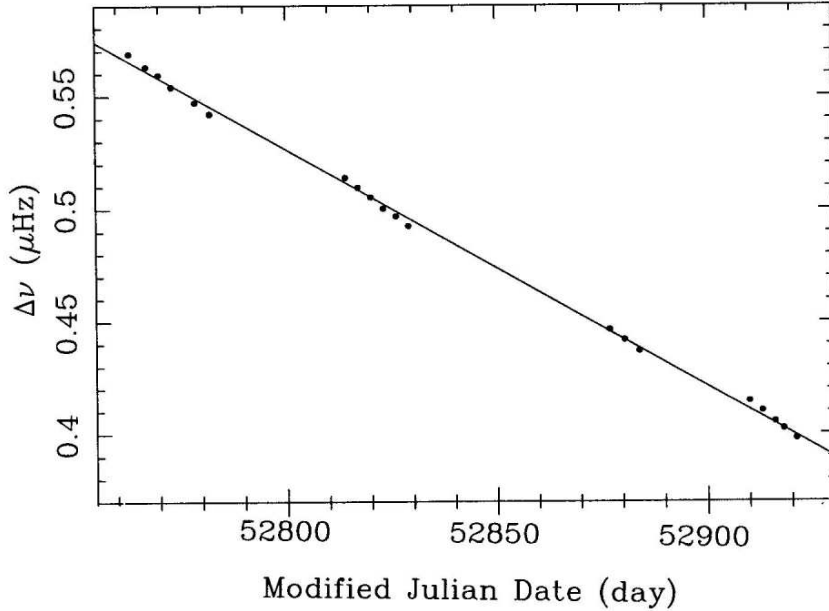


Figure 4: Variation of the rotational frequency of PSR B1931+24 over a 160-day period. The errors in the measurement of the data points are smaller than the size of the symbols. The best-fit straight-line through the points is shown, representing a frequency derivative  $d\nu/dt = -12.2 \times 10^{-15} \text{ Hz s}^{-1}$  (from [4]).

is the maximum derivative of the linear-polarization position angle in the average profile, which is obtained from the relationship describing the position angle  $\psi$  as a function of longitude  $\Phi$  (Fig. 7) [17]:

$$\tan \psi = \frac{\sin \beta \sin \Phi}{\sin \zeta \cos \beta - \cos \zeta \sin \beta \cos \Phi} \quad (3)$$

The factor  $D = \cos(W_{10}/2)$  is determined by the observed width  $W_{10}$  of the mean profile at the 10% level. The value of  $n$  can be estimated from the shape of the mean profile.

Now we consider some pulsars with measured polarization characteristics and known pulse profiles.

### **PSR B1931+24**

The radio pulsar PSR B1931+24 (J 1933+2421) emits pulses over five to ten days, then sharply is switched off, remaining undetectable over the next 25-30 days [19].

We have for this pulsar at a frequency close to 400 MHz [8,20]

$$C = 5.5, W_{10} = 37.5^\circ, D = 0.95, \text{ and } n \approx 2.$$

Thus, the problem of finding the angles  $\beta$ ,  $\zeta$ , and  $\theta$  in this case is reduced to solving the system of equations

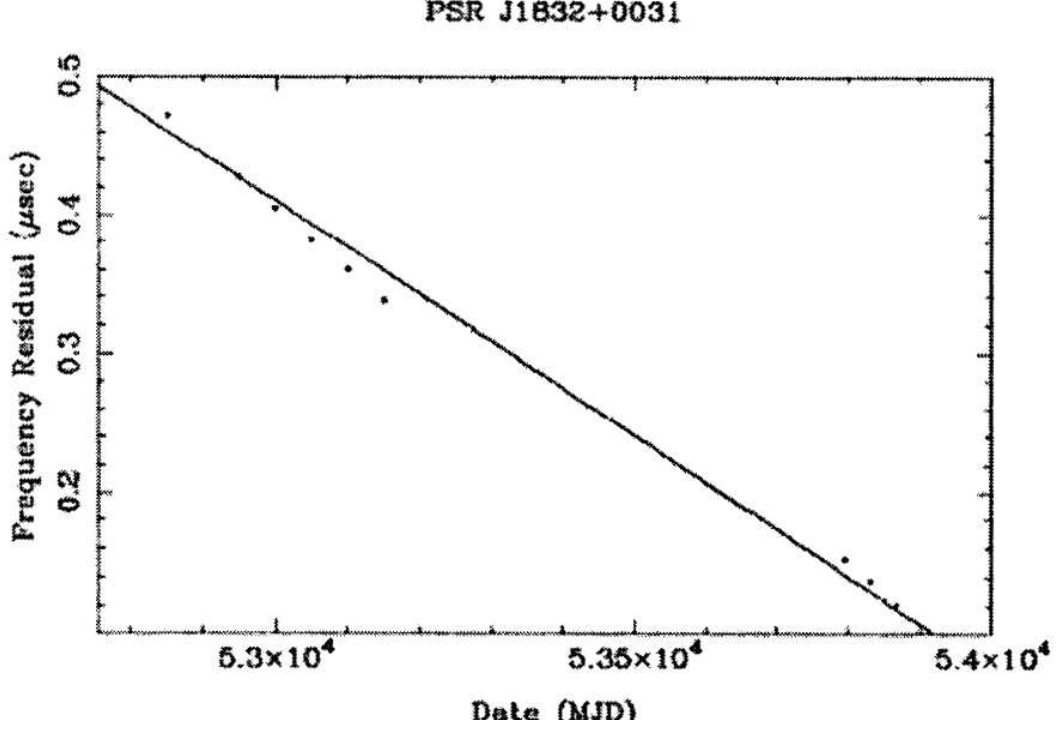


Figure 5: Variation of the rotational frequency of PSR J1832+0031.

$$\begin{aligned}
 \sin \beta &= 5.5 \sin(\zeta - \beta), \\
 \cos \theta &= \cos \zeta \cos \beta + 0.95 \sin \beta \sin \zeta, \\
 \theta &= 2(\zeta - \beta)
 \end{aligned} \tag{4}$$

The system (4) can be transformed to the following form [18]:

$$b_3 y^3 + b_2 y^2 + b_1 y + b_0 = 0, \tag{5}$$

$$\tan \beta = \frac{C(1 - y^2)^{1/2}}{1 + Cy}, \tag{6}$$

where  $y = \cos \zeta$  and coefficients  $b_i$  are determined as

$$\begin{aligned}
 b_3 &= 2C^3(1 - D)^2, \\
 b_2 &= C^4(1 - D)^2 + C^2(D^2 - 6D + 5) - 4, \\
 b_1 &= 2C[C^2(2 - D - D^2) - 2 - D], \\
 b_0 &= C^4(1 - D^2) - C^2(2 + D^2) + 1.
 \end{aligned} \tag{7}$$

For the observed parameters we obtain the following cubic equation for  $y$ :

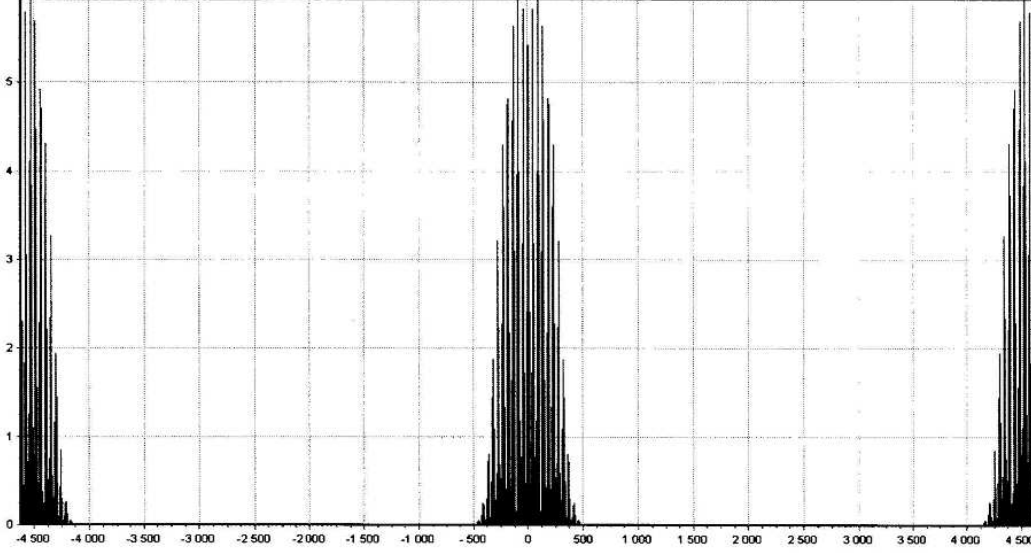


Figure 6: Simulated light curve of PSR J1819-1458 [14].

$$0.83y^3 + 4.41y^2 + 16.63y + 2.42 = 0, \quad (8)$$

which can be solved using the formula of Cardano [21]. This equation has only one real-valued root,  $y = -0.15$ , which corresponds to  $\zeta = 98^\circ.7$ . We obtain from (6) the value  $\beta = 88^\circ.2$ , and from the last equation of system (4),  $\theta = 21.0^\circ$ .

The analysis of equations under consideration shows that the main errors in the obtained solutions are caused by uncertainties in the measured value of  $C$ .

The error  $\Delta D = \sin(W_{10}/2)\Delta W_{10}/2$  is rather small ( $< 10^{-3}$ ) and can be excluded from the consideration. If we put  $\Delta C = 0.1$ , then for  $C = 5.4$  the angle  $\beta = 76^\circ.1$ ,  $\zeta = 86^\circ.5$  and for  $C = 5.6$   $\beta = 93^\circ.7$ ,  $\zeta = 110^\circ.0$ . Hence, this pulsar is nearly orthogonal rotator for  $C = 5.5 \pm 0.1$ .

The calculated values of angles ( $\zeta = 98^\circ.7$  and  $\beta = 88^\circ.2$ ) correspond to the pulsar geometry presented in Fig.8. Analysis of this geometry leads to the following conclusions.

1. Since PSR B1931+24 is an orthogonal rotator, pulses should be observed from both its poles, i.e., the true period of this pulsar should be twice the usual adopted value, and equals to  $P = 1.626$  s.
2. We expect different mean-profile shapes and integrated energies for even and odd pulses, since the line of sight changes its orientation with respect to the center of the radiation cone by  $3.6^\circ$  in the transition between the poles.
3. If the radiation cone is determined by open field lines for  $\beta \approx 90^\circ$ , its angular radius should be [22]

$$\theta = 0.54(r/r_{LC})^{1/2}, \quad (9)$$

where  $r$  is the distance from the center of the neutron star, and  $r_{LC} = cP/2\pi$  is the radius of the light cylinder. For the calculated value  $\theta = 21.0^\circ$ , we find that the radiation at a frequency of about 400 MHz is



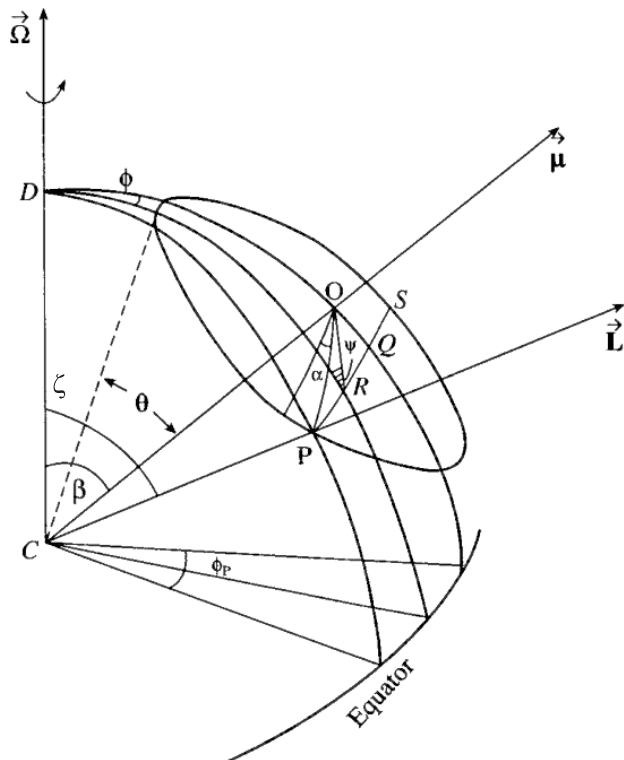


Figure 7: Geometry of the radiation cone in the polar cap model.

generated at a level  $r/r_{LC} = 0.46$ . For  $P = 1.626$  s, the corresponding distance is  $r = 3.57 \times 10^9$  cm.

As it was mentioned in the previous section, the possible cause of the switching on and off of the radiation in PSR B1931+24 was the presence of a relic disk around the pulsar. In particular it can precess with a period of about 30-40 days. If such a disk is in the equatorial region, it can occasionally "lock up" the pulsar radiation. Searches for traces of such a disk, e.g., of its infrared radiation, are necessary. The possible existence of relic disks around pulsars with transient radiation was also considered in [15,16]. A decrease in  $dP/dt$  can also be related to the presence of plasma of the relic disk at the times of switching off. Partial or full blocking of the radiation inside the magnetosphere decreases the loss of angular momentum of the pulsar. Meanwhile, the escape of relativistic particles to the surrounding plasma partially persists, and this pulsar wind provides a spin-down in the periods of switching off of the observed radiation. A small amount of disk accretion also can spin up the neutron star, decreasing  $dP/dt$  somewhat. Generally speaking, the presence of precession is not a mandatory element in the proposed model. Locking and unlocking of the radiation cone could be due to inhomogeneity of the surrounding disk. In this case, due to differential disk rotation, dense inhomogeneities sometimes fall in the line of sight, hindering the propagation of the pulsar radiation. Essentially, this type of situation can be observed in, e.g., other Rotating Radio Transients (RRATs).

Beskin and Nochrina [23] discussed the role of current losses in the magnetosphere of PSR B1931+24. These losses could account for the observed jump  $(d\Omega/dt)_{on}/(d\Omega/dt)_{off} = 1.5$ . In "off" periods, the magnetosphere is not filled with plasma, and angular-momentum losses are due to magneto-dipole radiation. When the radiation

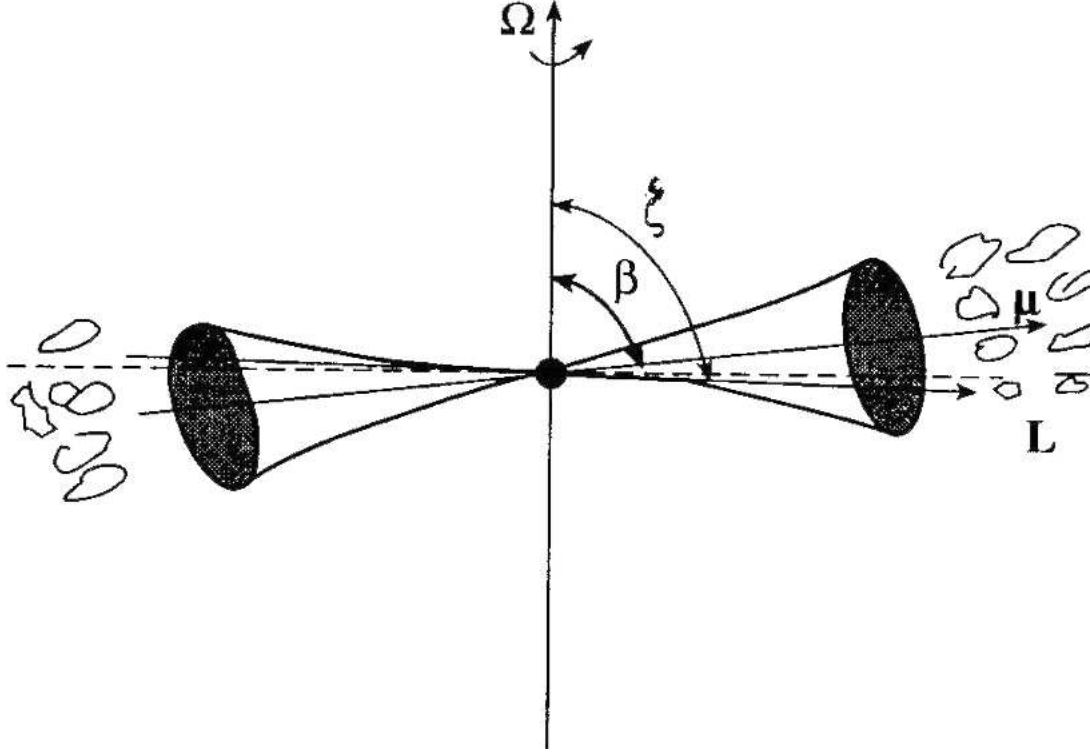


Figure 8: Radiation geometry for the pulsar PSR B1931+24.

is observed, braking of the neutron star is due to current losses; the ratio of these energy losses is then

$$\frac{W_{md}}{W_c} = \frac{B_s^2 R^6 \Omega^4 \sin^2 \beta}{6c^3} : \frac{f_*^2 B_s^2 R^6 \Omega^4 \cos^2 \beta}{4c^3} = \frac{2 \tan^2 \beta}{3 f_*^2} \quad (10)$$

However, using  $\beta = 88^\circ.2$  and the dimensionless area of the polar cap  $f_* = 1.96$ , we obtain

$$(d\Omega/dt)_{on}/(d\Omega/dt)_{off} = W_{md}/W_c = 264.$$

Thus, magneto-dipole losses in the "on" state of PSR B1931+24 should be considerably greater than the current losses in the "off" state.

### PSR B0656+14

Weltewrede et al. [6] proposed that the burst-like character of the radiation of PSR B0656+14 is similar to the behavior of RRATs. In this connection, it is interesting to estimate the angles between its axes. We could use the system (1), but, in the case of PSR B0656+14, it was sufficient to obtain simpler estimates based on the profile shape and derivative of the polarization position angle. For this pulsar, the maximum derivative at frequencies near 400 MHz is  $C = 1.28$  [20]. For such a small value of  $C$ , we can use the formula [2, 3]

$$C \geq 3.24 \sin \beta, \quad (11)$$

which yields  $\beta < 23^\circ.3$ . The conclusion that the angle  $\beta$  is small also follows from the simple (one component) shape of the pulsar pulse. Indeed, we have in this case [18]

$$\zeta - \beta = 3\theta/4 \quad (12)$$

On the other hand, it follows from Fig. 9 that

$$\zeta - \beta = \theta \sin \alpha \quad (13)$$

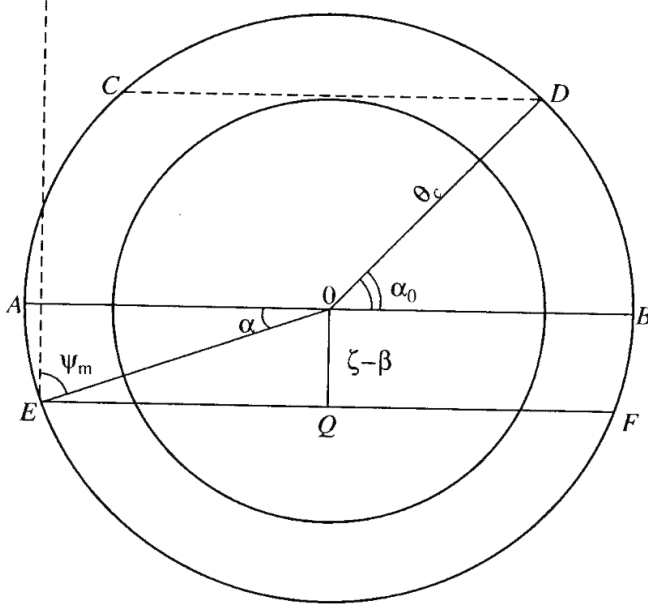


Figure 9: Cross section of the radiation cone.

As a result, for  $W_{10} = 35^\circ.3$  [20], we obtain  $\theta = 17^\circ.8$ ,  $\zeta - \beta = 13^\circ.3$ , and it follows from the first equation of (1) that  $\beta = 17^\circ.2$ . These estimates demonstrate that  $\beta \sim 20^\circ$  in PSR B0656+14, and this pulsar is a "normal" pulsar and not a transient. The variations in its radiation (including outbursts) have intrinsic origins, related to the particulars of its radiation mechanism, not its specific geometry or the presence of a relic disk.

### PSR J 1810-197

Kramer et al. [24] present polarization observations of the radio emitting magnetar AXP J1810-197. Its emission is nearly 80 – 95% polarized. The position angle swing has a low maximal slope  $C \leq 1$ . Using the first equation from the system (1) or the inequality (11), we conclude that  $\beta < 20^\circ$ . Hence, the main suggestion of the drift model is fulfilled for this object. It is nearly aligned rotator with the modulation of emission like presented in Fig. 3. The solution for all parameters by using profiles from [24] is rather uncertain because we don't know a real rotation period of this pulsar and can't calculate precisely the parameters  $D$  and  $C$  to use the system (1).

## 4 Conclusions and discussion

1. As the example of the PSR J 1810-197 shows the drift model can be used for the description of the peculiarities of AXP emission. In this model real rotation periods must be much shorter than observed intervals between the successive pulses. The smallness of the angle  $\beta$  provides very wide X-ray pulses but very narrow radio pulses with extremely narrow sub-pulses.

2. The angles between the various axes in the pulsar PSR B1931+24 estimated from the observed profile shape and polarization data indicate that this pulsar is an orthogonal rotator. The magnetic moment is inclined to the rotation axis by the angle  $\beta = 88^\circ.2$ , while the angle between the line of sight and the rotation axis is  $\zeta = 98^\circ.7$ .

3. The possible origin of the switching on and off of the observed radio emission of the pulsar is precession of a relic disk with a period of about 35 days.

4. For other pulsars with prolonged switching off of the observed radiation (transients), polarization measurements are required to enable estimation of the angles between their axes, and to test whether they are orthogonal rotators.

If all transients prove to be orthogonal rotators, a common picture for them could be as follows. A relic disk almost continually screens the radiation of the neutron star from us, but, owing to the disk's inhomogeneity, it can have gaps, through which the pulses can "leak out" toward the observer during a limited time.

To check the model proposed in this paper, it is extremely important to search for manifestations of relic disks around transients and periodicity in the variations of their radiation. The results obtained in [16] inspire optimism. Transient objects are fairly young ( $\tau = P/(2dP/dt) \sim 10^6$  years); hopefully, the material that was ejected during the supernova explosion has not yet completely dispersed in the interstellar medium.

Probably there is the bimodality of anomalous pulsars. AXPs, SGRs and some radio transients belong to the population of aligned rotators with the angle between the rotation axis and the magnetic moment  $\beta < 20^\circ$ . These objects are described by the drift model, and their observed periods are connected with periodicity of drift waves. Other sources have  $\beta \sim 90^\circ$ , and switchings on and switchings off of their radiation are caused by accretion phenomena connected with a relic (debris) disc surrounding them.

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